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Introduction

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Author for correspondence:
P. G. Tucker
e-mail: pgt23@cam.ac.uk

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Aerodynamics, computers and the environment

P. G. Tucker[1] and J. R. DeBonis[2]

[1]Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK
[2]NASA Glenn Research Center, Cleveland, OH 44135, USA

1. Introduction

We are faced with global warming and dramatic increases in the world aircraft fleet. Computing power continues to inexorably rise, and machines are now powerful enough to make new technological breakthroughs in the aerospace industry. This Theme Issue seeks to explore how computers should be used in future and how they may impact critical problems in aviation and its impact on the environment. However, the work also has wider relevance to the general fields of transport and energy.

The environmental impact of aircraft with respect to emissions, including noise, is an area of critical importance. In many instances, aerodynamic performance and noise are intrinsically linked through turbulence. Go to any major international conference on turbulence, and one would be hard pressed to find many delegates who could agree on a definition of what turbulence actually is. As the Nobel prize winner Richard Feynman said 'Turbulence is the last great unsolved problem in classical physics'. This makes the mathematical modelling of turbulence challenging. Equations complete enough to virtually exactly describe turbulent flow—the Navier–Stokes equations—have been available for over a century. Until recently, the standard practice in computational fluid dynamics (CFD) is to solve a time-averaged version of the Navier–Stokes equations, using a simplified model to represent the turbulence—the Reynolds-averaged Navier–Stokes (RANS) approach. However, computing powers have increased to the point where one can seriously consider the near-direct solution[1] (NDS) of these equations for practically relevant flows. Thus, armed with high-performance computing (HPC), modern computer graphics and analysis tools we can now, for practically relevant systems, unlock turbulence's

[1]This term is intended to encompass large eddy simulation and quasi-direct numerical simulation.

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secrets and thus intelligently manipulate the turbulent flow field, to improve performance and so address global environmental challenges.

This situation was not unforeseen. Chapman (see [1]), director of aeronautics at NASA, proposed, using generally well-founded scientific arguments, that when computers reached 10^{14} FLOPS (floating point operations per second) we could perform NDS that would begin to rival aerodynamic tests. Modern HPC provision now exceeds Chapman's expectations reaching petascale with exascale computing due around 2018. Hence, now the ability to directly predict turbulence, for complex engineering systems, without recourse to accuracy reducing assumptions is close at hand. Computer-processing speeds have increased by a factor of around one million in the past 25 years (see Jameson [2]), and continued improvements are expected.

Currently, flow physics insights from NDS are allowing the improvement of reduced-order mathematical models for design. In addition, simulations that potentially offer greater accuracy than tremendously expensive rig tests are now emerging. A notable shoot from the emerging era is work of Morton *et al*. [3] (US Air force Laboratory), who performed an NDS variant for an F/A-18 fighter configuration. Tail buffet was explored, and successful comparison made with real flight data. There are many other examples.

Thus, after waiting with eager expectation, for several decades, Chapman's prophecy is coming closer to fulfilment. This Theme Issue explores what is needed to complete the fulfilment, how will things gradually change as the fulfilment is approached, what might the new era look like and when it will arrive. Obviously, what is meant by fulfilment is a complex thing, because aerospace systems involve a wide range of components with very different flows and degrees of coupling/dependence with other components. Hence, different flows will come to fruition at vastly different times.

The Theme Issue comprises 12 papers exploring the abovementioned theme. The papers typically look at the status of computational modelling around 2030–2035.

2. Aeroengines

Menzies [4] at Rolls-Royce plc focuses on aeroengines. The emissions targets in terms of CO_2, NO_x and noise are defined. The paper has a positive message on the future role of CFD and its particular importance for simulating coupled airframe and engine interactions where rig tests will be especially expensive.

In relation to aeroengines, Bistetti *et al*.'s [5] paper shows how direct numerical simulation can enhance our understanding of the science of pollution generation. The focus is very much on soot, which is of critical environmental importance but not what one immediately expects when considering environmental issues. The use of direct numerical simulation to refine NDS approaches such as large eddy simulation is discussed.

Designing stable compressors is a critical issue for axial gas turbines, and so is the focus of the strongly prophetic paper by Gourdain *et al*. [6]. Currently, studying compressor stability is a great challenge for CFD. Interestingly, it is pointed out that the problem sizes being tackled substantially lag the growth in the power of computers. The potential for the gas lattice Boltzmann method for NDS is identified. There is discussion on how research in relation to Google and Facebook may offer assistance with the issue of dealing with the massive datasets from NDS. This is also discussed in the paper by Lele & Nichols [7]. Specific numerical challenges relating to turbomachinery—such as phase lagged boundary conditions—are discussed and potential algorithms to overcome them are given.

It is well known that to improve the performance of gas turbine aeroengines it is necessary to increase the temperature of the combustion gases entering the turbine. However, these, even now, are well above the melting temperatures of ordinary metals. Hence, turbine blade cooling is a critical area. Tafti *et al*. [8] discuss turbine blade cooling. The strong benefits of improved numerical predictions on reducing environmental impact are clearly made. The paper offers a balanced, positive, perspective on the future outlook for NDS for internal blade cooling

modelling. Notably, cooling flows typically seek to produce large-scale turbulent structures that enhance mixing. Hence, as noted in that paper, such flows are well suited to NDS. Notably, such flows are Reynolds number independent and so do not suffer from the extreme growth in computational cost with Reynolds number found in zones with attached boundary layers. Fortunately for NDS, the low-pressure turbine, which provides around 80% of the thrust of aeroengines, involves modest Reynolds number ($Re \sim 5 \times 10^5$ for a medium-sized gas turbine engine). Hence, as acknowledged by Medic & Sharma [9] (United Technologies Research Centre), this is an area where NDS could also already be used in design in some sense. However, for the flows found in airframes, the Reynolds numbers are substantially higher, creating a challenge of a massively different scale. This aspect is outlined by Slotnick *et al*. [10].

3. Airframes

Slotnick, at Boeing, and a range of co-workers again outline the serious environmental challenges posed by the increasing use of air transport. For example, the forecast of 1.5 billion tonnes of annual CO_2 emissions by 2025 is given. The paper has a strong focus on airframes, but there is some discussion on propulsion modelling with Pratt and Whitney input. The need for validation data is discussed and this is an important point. The authors also point out that in order to bring the transformative change in CFD for industry to fruition, there is a need to link education in computer science to sustainable aviation for future graduates and postgraduates. In addition, the need for more investment in applied mathematics and computer science in general is noted. This all seems critical to realize the bold vision identified by Slotnick *et al*. The need for international collaboration is also stressed. A wealth of new computer science and algorithms are identified in the paper. The recent stagnation of CFD methods is noted. Capabilities for the management of large databases are discussed, and the need for methods to merge data from various sources such as measurements, high fidelity CFD and low-order simulation results. In accord with Giles & Reguly [11], it is also stressed that it is necessary to keep an eye on novel computational technologies such as quantum and molecular computing. It is further pointed out that sustained exaFLOPS (10^{18} operations a second) for an actual CFD calculation will probably not be achieved until at least 2020. Evidently, current predictions suggest 30 exaFLOPS should be possible in 2030. Like Gourdain *et al*. and also Lele & Nichols [7], a future role for lattice Boltzmann methods is noted. A greater understanding of these methods' numerical traits might well be helpful.

Deck *et al*. [12] present a range of exciting cutting-edge examples showing the application of hybrid RANS–NDS to various airframe-related flows. The zones where RANS and NDS are used, and the local modelling methodologies are solidly rationally based. This paper very much shows how NDS approaches are being actively used now for real aerospace systems and hence makes the future prospects even more exciting.

NDS approaches open up the possibility of reliably exploring flow control and deeply understanding how the flow control strategy interacts with the flow field. Fujii [13], at the Japanese Aerospace Exploration Agency, gives a positive aerospace perspective for the use of NDS to explore flow control. The paper focuses on plasma actuators and their use on high lift-configured aerofoils. Simulations use the Japanese petaFLOPS supercomputer 'K'. This facility allows a volume of large (reaching one billion cells) high-order simulations to be made. Strong potential for the use of NDS to reduce the environmental impact of aircraft at low Reynolds numbers is identified in this paper. Fujii sees that the time to move from what he describes as 'geometry design' to 'device design' is close. The latter term reflects that a flat plate with control devices can replicate the role of an aerofoil and that with modem supercomputers this radical step can be realized.

4. Computers and algorithms

The paper by Larsson & Wang [14] gives some interesting insights into pressing technological needs to allow the use of design optimization with NDS. There is discussion on space–time

parallelization, the performance of temporal schemes and the potential for hybrid implicit–explicit temporal schemes and the zonalization of such methods. The discussion on the use of design optimization with NDS and the problems faced when using adjoint design optimization for NDS-based design make a very interesting contribution to the issue.

A substantial number of papers identify that high-order methods have potential benefits, such as, for example, reducing the amount of data that needs to be transferred in massively parallel simulations. In addition, for certain methods, there is the potential for less grid sensitivity. Hence, the paper by Wang [15], considering high-order methods, seems especially important. Wang identifies grid generation for high order as a critical component. As noted in the paper, the current scarcity of high-order solvers, particularly commercial, stunts the development of high-order grid generation. Numerical stiffness and storage, scaling with scheme order to the power six are identified as potential research challenges. Perhaps another area where work is required is exploring the properties of high-order schemes at high wave numbers and hence how they will interact with subgrid-scale parametrizations. Certain high-order schemes appear dissipative at high wave numbers. However, this trait could advantageously be turned to being used as the dissipative component of subgrid-scale models. Hence, there seems a need for modified equation analysis for more exotic high-order schemes.

Giles & Reguly [11] look at trends in HPC. As well as looking at hardware, the paper explores software forms necessary to be compatible with future hardware and offers advice for code developers. It is noted that the life of a piece of CFD software is massive relative to the short time scales over which hardware is currently evolving. Advice on dealing with this is given. Interesting potential algorithms for reducing data transfer are discussed, this being seen as the critical issue.

Clearly, computer power will always be limited and hence some form of turbulence modelling needed. Piomelli [16] gives a nice survey of subgrid modelling with NDS, hybrid RANS–NDS approaches and related methods. Algorithmic needs are also explored. The critical issue of the way the numerical scheme, grid and the subgrid-scale model work together, and that it is vital to get this aspect right is discussed. Use of integral scale estimates to design grids, so that the resolution is effectively uniform, is proposed.

5. Aeroacoustics

The paper by Lele & Nichols [7]—a second golden age of aeroacoustics—has a wide-looking perspective that encompasses some practical engineering needs to deep issues associated with modelling and performing large-scale acoustic simulations. Computational algorithms for aeroacoustics are discussed. Examples of cutting-edge simulations are given. Most areas of aerospace noise are considered, such as turbomachinery, including jet, fan and turbine noise. For airframes: slat, trailing edge and landing gear noise are addressed. In addition, propulsion–airframe interactions are considered. Hence, the need for large-scale coupled simulations and how these will enforce the need to retain low-order models are addressed. In addition, the paper has a section dedicated to data-driven modelling and uncertainty quantification. Lele and Nichols explore algorithms. They classify simulation algorithms that are likely to remain important and how these need to be considered in the future design of hardware. In addition, new algorithms emerging that could help with massively parallel simulations are covered. Lele and Nichols are prophetic, indicating that eddy resolving simulations could be used in aerospace for non-wall bounded flows in design in the next 5–10 years. The paper wisely seeks problems that are readily amenable to NDS, for example high-speed jets, where the noise from the large scales, which dominate the noise generation process, is relatively easy to deal with. As would be expected the severe demands for wall bounded flows are noted.

6. The future

Clearly, with the closer integration of engines and airframes, to meet the pressing environmental challenges arising from the growth of air transport, the need for coupled simulations grows.

This and the high Reynolds numbers found in many areas of aerospace applications will impose substantial modelling content on simulations. However, it is clear from the contributions to this Theme Issue that the simulation environment around 2030 and beyond will be very different to what it is now. This will mean that revised best practices will required, because there will be a considerable migration to NDS and hybridizations of it (with current modelling methods) and this will need revised CFD best practices. Although such aspects seem dull, they are of critical importance. Currently, where NDS is attempted, for more industrial applications, frequently the grid resolutions used are inappropriate. Clearly, as also pointed out by Slotnick *et al*., there is a pressing need to reignite research into algorithms, computer science and applied mathematical methods, related to CFD. This area has tended to stagnate and has not matched the expected pace of developments in the Chapman era. It is clear from this issue that CFD has an increasing and pivotal role in the design of clean, silent and thus environmentally friendly aircraft.

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